Lifetime estimation of a time projection chamber X-ray polarimeter

Joanne E. Hill*[a], J. Kevin Black[a,b], Lubos Brieda[a,c], Patsy L. Dickens[a,d], Kristina Montt de Garcia[a], Douglas L. Hawk[a,e], Asami Hayato[f], Keith Jahoda[a], Jelila Mohammed[a].
[a]NASA Goddard Space Flight Center, Greenbelt MD 20771, USA; [b]Rock Creek Scientific, 1400 East-West Hwy, Silver Spring, MD, 20910, USA; [c]Millennium Engineering and Integration, Inc., 2231 Crystal Drive Suite 711, Arlington, VA 2202, USA; [d]SGT Inc., 7515 Mission Drive, Lanham, MD 20706, USA; [e]ATK Space, Beltsville, MD, USA; [f]RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan.

ABSTRACT

The Gravity and Extreme Magnetism Small Explorer (GEMS) X-ray polarimeter Instrument (XPI) was designed to measure the polarization of 23 sources over the course of its 9 month mission. The XPI design consists of two telescopes each with a polarimeter assembly at the focus of a grazing incidence mirror. To make sensitive polarization measurements the GEMS Polarimeter Assembly (PA) employed a gas detection system based on a Time Projection Chamber (TPC) technique. Gas detectors are inherently at risk of degraded performance arising from contamination from outgassing of internal detector components or due to loss of gas.

This paper describes the design and the materials used to build a prototype of the flight polarimeter with the required GEMS lifetime. We report the results from outgassing measurements of the polarimeter subassemblies and assemblies, enclosure seal tests, life tests, and performance tests that demonstrate that the GEMS lifetime is achievable. Finally we report performance measurements and the lifetime enhancement from the use of a getter.

Keywords: Dimethyl ether, polarimeter, time-projection chamber, Gravity and Extreme Magnetism SMEX, outgassing.

1. INTRODUCTION

1.1 The GEMS Polarimeter

The Polarimeter Assembly (PA) is the X-ray detection and measurement sub-system of the X-ray Polarimeter Instrument. The assembly is comprised of a polarimeter that detects and measures the X-ray polarization and energy, a modulated X-ray source (MXS) for calibrating the polarimeter, the high-voltage distribution (HD) card that provides HV to the polarimeter, the polarimeter readout (PR) card that reads out the data from the polarimeter and processes it and the electronics enclosure/radiator that houses the electronics and ensures the heat is radiated out to space and not into the polarimeter (see Figure 1 and Figure 2).

The polarimeter mounting plate is a wedge shape with an angle of 30 degrees. This is to position the two polarimeters orthogonal to each other when mounted on the optical bench panels, which are at 60 degrees to each other. This strategic positioning of the two polarimeters is an added precaution to mitigate against systematic effects.

1.2 Polarimeter Design

The polarimeter is designed to study the polarization of X-rays emitted by astronomical objects such as black holes and neutron stars[7]. It has a sealed gas volume that contains the detector components and therefore the most challenging lifetime requirements are levied on the polarimeter.

In each polarimeter there are four detectors consisting of a readout board (ROB) and a Gas Electron Multiplier (GEM), six field cage elements and four drift planes. The polarimeter is a sealed gas volume that contains 190 T of Dimethyl Ether (DME). The polarimeter also has a pressure transducer to monitor the pressure, a getter and getter valve assembly that maintains gas cleanliness, a purge pinch-off tube to allow for gas flow during bake-out and a pump-out valve that allows for removal and adding of gas during ground operations and seals for flight. The polarimeter contains two beryllium windows, the optical window that allows the X-rays from the mirrors to penetrate into the volume and the

*joanne.e.hill@nasa.gov; phone 1 301 286-0572; fax 1 301 286-7230

Modulated X-ray Source (MXS) window that allows the calibration X-rays to enter the detector volume. X-rays interact with the DME molecules and generate photoelectrons. The electrons are then moved towards an electron multiplier (GEM) under a uniform electric field and the signal is collected on a readout board (ROB)[1][5].

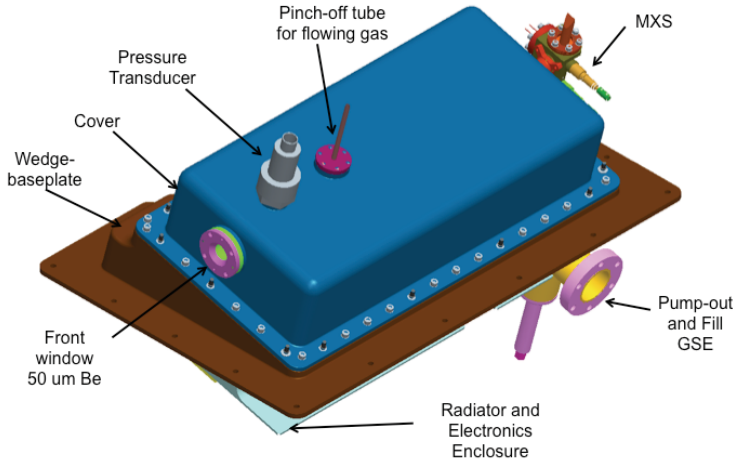


Figure 1 The Polarimeter Assembly Sub-system

1.3 Lifetime Definition

The GEMS nominal mission is 10 months on orbit with the extended mission requiring 25 months. The final opportunity for a polarimeter gas exchange is following observatory thermal vacuum testing that will be completed 6 months prior to launch. This leads to a nominal lifetime of 16 months and an extended lifetime of 31 months. While the extended mission is not a driving requirement it will be used to calculate the extended life-performance.

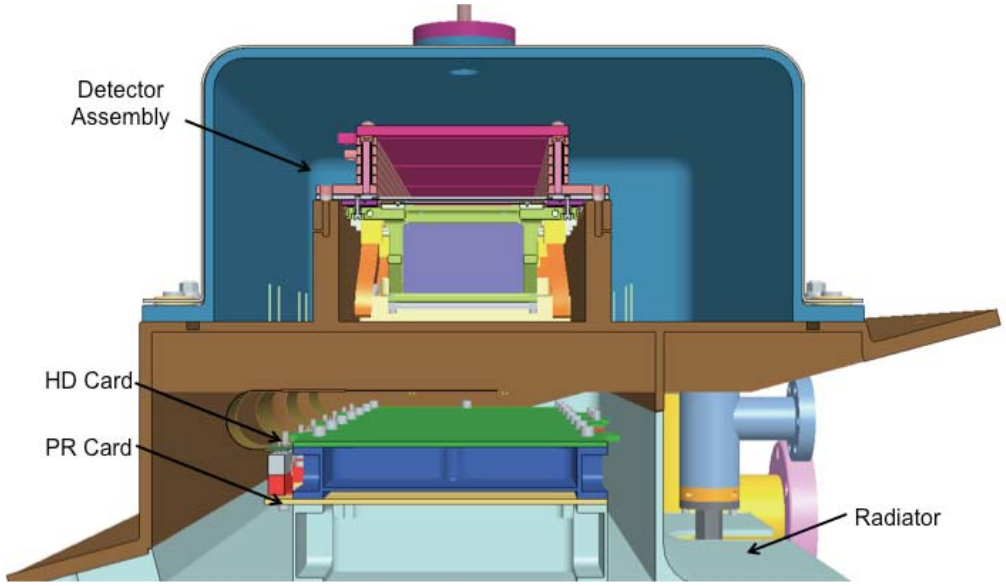


Figure 2 The Polarimeter Assembly Subsystem (Section view)

1.4 Lifetime Requirement

The polarimeter polarization sensitivity depends on several parameters, the quantum efficiency of the gas, the energy resolution and the gain. The Polarimeter lifetime is defined as the time before the energy resolution increases to more than 30% at 6 keV for an average drift distance of 0.8 cm or the time before the beginning of life (BOL) gain falls to 10%, whichever occurs sooner.

2. POLARIMETER DESCRIPTION

2.1 Gas Selection

To maximize the sensitivity in the 2-10 keV band, the active medium of the polarimeter is dimethyl ether (DME) at 190 Torr. DME is composed of low-Z elements (carbon and oxygen) and has the lowest electron diffusion and drift velocity of any known proportional counter gas. Photoelectrons created from X-ray absorption by lower-Z elements have greater range and are highly modulated, as the Auger electron has a smaller percentage of the incident energy and the photoelectron is more likely to be emitted from an s-orbital, giving a pure $\cos^2\theta$ distribution.

The ability to image the photoelectron tracks is ultimately limited by electron diffusion and the pixel size. Low-diffusion DME at 190 Torr gives excellent image resolution with a strip pitch that can be readily achieved with a robust, commercially available technology.

DME is inherently radiation hard because of its large oxygen content, which prevents polymer chains from forming due to radiation damage.

2.2 Materials selection

It has been demonstrated that as long as materials are carefully selected, detectors with both with DME mixtures [4] and pure DME [9] can be long lived.

Material selection for the interior components of the polarimeter is therefore critical to the lifetime of the detector. Where possible, components inside the gas volume are fabricated from metal that are gold plated over a nickel strike (except for the stainless steel fasteners). The gold plating reduces the secondary background events from metals inside the gas volume that have k-shell electrons in the GEMS band-pass. In addition, the gold is inert and protects from any reactions with the DME.

No epoxies are used on the interior of the polarimeter, only solder and brazing processes are implemented to make connections. Flux-less solder with IPA dissolvable high vacuum flux is used in all cases so that it can be washed away at the end of the solder steps.

The premise of the material selection for the non-metallic components on the interior of the polarimeter was to minimize the number of different materials in order to reduce the likelihood of inadvertent reactions from long-term exposure to DME. In addition, fewer materials will limit the number of different outgassing products inside the gas volume.

Liquid Crystal Polymer (LCP) is used in the Gas Electron Multipliers (GEMs) due to its extremely low water absorption (0.04% in 24 hours), chemical resistance (98.7%), outstanding isolation and dimensional stability[10][11]. The nominal thickness of the GEM LCP is 100 μm with 5 μm of copper cladding on either side. 70 μm holes are laser drilled in a hexagonal pattern on a 140 μm pitch. The melting point of LCP is 314 °C and the nominal max bake-out temperature is 200 °C.

Because the LCP was implemented in the GEM fabrication LCP was also utilised elsewhere for the necessary electrical circuits, such as the detector strips and the flex cable carrying the signals from the readout board through the D-sub feed-through in the baseplate of the gas enclosure. The LCP implemented in the strips and flex cable is Rogers Ultralam 3850. Both the strip and the flex cable designs use multiple layers, requiring lamination. The lamination layer is also LCP but Rogers Ultralam 3908. In both cases the nominal thickness of the LCP is 25 μm however the cable is multilayer.

A structural non-conducting material is needed to isolate fasteners and electrodes at various voltages within the gas volume. Polyetheretherkeytone (PEEK) unfilled and 30% glass-filled was selected for use in the cases where LCP cannot be used. It is extremely chemically resistant, has excellent mechanical properties and is known to be compatible with DME in proportional counters [8]. It is one of the few plastics compatible with ultra-high vacuum applications. The readout board connectors are made from PEEK that can be baked up to 250 °C and have been validated for vacuum systems down to 10^{-10} Torr. Water absorption in PEEK is 0.1% in 24 hours.

The other non-metallic substances contained in the gas volume are the Low-Temperature Co-fired Ceramic (LTCC) ASIC board, the Silicon APV-25 ASIC and AD590 temperature sensor and the quartz fan-in on the ASIC board. Ferro A6 LTCC was chosen for the ASIC circuit board due to its flight heritage and its low CTE. It is constructed into a multilayer board that can be soldered to a metal bracket thus avoiding the use of epoxy.

The ASIC and the AD590 die are delivered without metallization on the back and therefore both the ASIC and the AD590 are brazed to a Molybdenum shim with a SiAu solder and then soldered to the LTCC board.

Fused silica (quartz) was selected for the ultra fine-line fan-in due to its low dielectric constant to minimize noise. The fan-in is also soldered to the LTCC ASIC board.

The resistors and capacitors on the LTCC board (on the back of Figure 3, right) are all thick and thin film parts, with most having a gold finish.

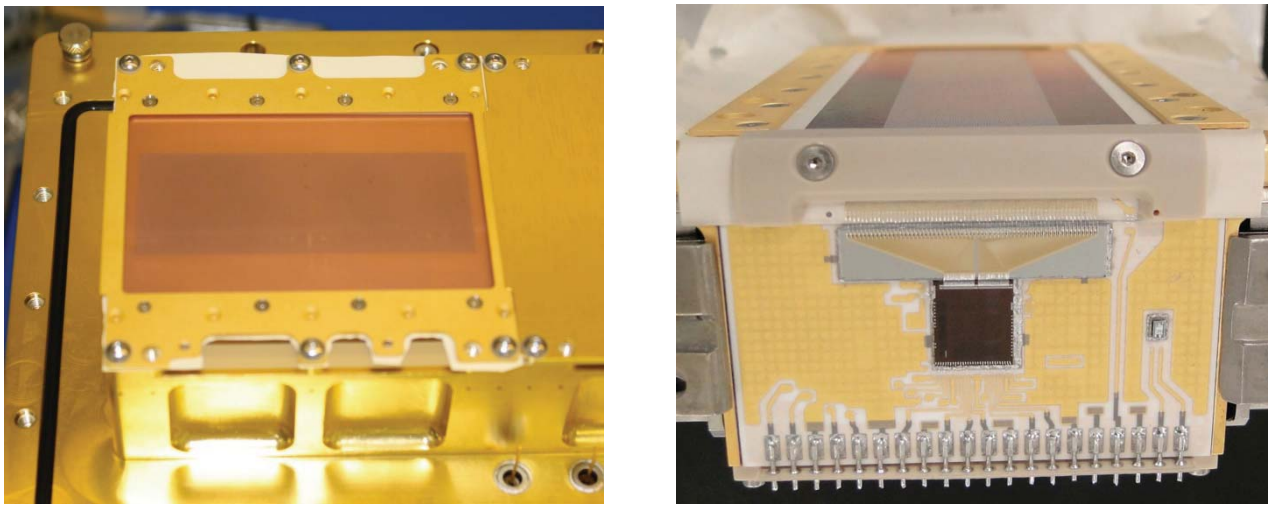


Figure 3 Left: Gas Electron Multiplier (GEM) mounted in gold-plated Ti frames. Right: Readout board (ROB) with LCP strips, gold-plated Ti frames, LTCC ASIC board, Si ASIC and AD590, and quartz fan-in.

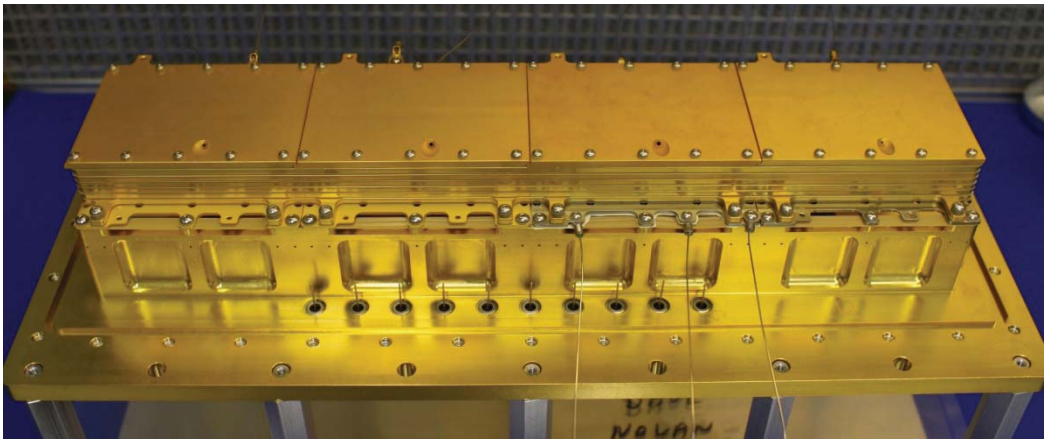


Figure 4 Gold-plated magnesium drift and field cage assembly mounted on top of the GEM-ROB assemblies inside the gas volume.

2.3 Metal finishes.

There is much discussion in the literature regarding whether the metal surface finish can affect the rate of outgassing of moisture from the surface e.g.[12]. However, historically at GSFC (SAM, XTE and WFC3) all high vacuum and gas detectors have implemented a highly polished finish on the interior to the gas or vacuum volume with the expectation that it improves the rate at which the moisture is removed from the surface during bake-out and purge.

The finishes for the flight polarimeter are better than 32 μinches. The sealing surfaces, were hand polished to ~6-7 μinches prior to plating to ensure all tooling marks are removed to provide an optimum sealing surface.

3. POSSIBLE FAILURE MECHANISMS

The polarimeter lifetime can be affected by several mechanisms; the ones that are specific to a gas polarimeter are outlined in the sections below.

3.1 Outgassing of components inside the polarimeter:

Outgassing of materials inside the polarimeter gas volume reduces the gain and degrades the energy resolution through the loss of electrons to molecules with high electron affinity. The presence of contaminants can also change the drift velocity and introduce systematic errors in the estimation of the initial photoelectron direction.

A discussion of outgassing measurements is provided in Section 6.

3.2 Polarimeter degradation due to on-orbit radiation damage

Radiation lifetime can be characterized in (at least) two ways. The estimated total charge accumulation over the GEMS mission accounting for both X-rays and particle induced events is 0.001 mC/mm^2; the total fluence of heavy ions or penetrating particles can also be estimated where the first estimate is related to the second by the number of primary ionizations and the anticipated gain.

Iwahashi et al., [6] have evaluated the lifetime of SciEnergy GEMs to large fluences of both heavy ions and protons and find that the GEM itself can withstand decades of exposure in a low earth orbit similar to GEMS.

A similar conclusion can be drawn by comparing ground-based studies of the accumulated charge densities expected for detectors at the Large Hadron Collider (LHC). The benchmark performance for LHC detectors is 100 mC/cm (dose calculated per unit length of readout electrode, appropriate for Micro-Strip Gas Chambers (MSGC)) that corresponds to charge densities of 1000 – 10,000 mC/mm^2 (range corresponds to strip pitches of 0.1 – 1 mm). By any measure of accumulated charge, the high-energy benchmark is $>10^5$ times greater than the accumulated charge expected for the GEMS mission lifetime.

The total charge accumulated at the GEM can be used as an upper limit to the amount of charge collected on the readout strips, as there is no multiplication in the transfer gap. Ground-based studies suggest that deposits are less likely where the fields are lower, which is the case in the transfer gap.

3.3 DME degradation due to radiation

A permanent degradation of the operating characteristics of gas detectors due to sustained radiation is a well-known problem. Bouclier [1] identifies two mechanisms that lead to detector aging: (1) formation of polymers within the avalanche plasma, and (2) direct deposition of heavy molecules on the electrodes. In the first case, polymers could be formed from impurities or the main counter gas, while the second applies primarily to gas pollutants.

Bouclier [1] present a review of many studies, acknowledging that there is a “diversity of results obtained by various groups” and that “The detectors’ lifetime appears to depend critically on the nature and purity of the gas mixture, on the materials used in the chamber assembly and in the gas system, on the nature of the electrodes and on the electric field strength at their surface”. Most of the high-energy studies involve MSGC, which have higher fields at the multiplication anodes (strips or wires) than the GEM electrodes.

Examples of long-lived detectors both with DME mixtures [4] and pure DME [9] demonstrate that clean detectors with carefully chosen materials can meet the LHC benchmark. Materials and processing for GEMS are consistent with the ground experience, with the caveat that GEMS employs sealed detectors while the ground-based experiments often involve flow counters. (Flow counters ensure ~constant concentrations of impurities, while sealed counters may have increasing concentrations.)

Capeans [3] figure 10 compares the performance of a clean wire-counter in Ar-DME to Ar-CH_4 for various radiation doses. The data show that DME is much more resistant to aging than Methane. This is a strong indication that using DME in the GEMS polarimeter will not be degraded over its lifetime as the Rossi X-ray Timing Explorer (RXTE), which uses methane, has survived for more than a decade in Low Earth Orbit.

3.4 Loss of gas on orbit

The polarimeter requires bi-directional seals. If the seals are inadequate the DME gas will leak out on orbit and during thermal vacuum testing thereby reducing the quantum efficiency, affecting the gain and reducing the pressure such that the photoelectron tracks will get larger. These effects will change the calibration and at some point the sensitivity will be reduced below the requirement. A discussion of testing for the flight seals is provided in Section 6.4.

4. CALCULATION OF END OF PRIMARY MISSION (EOPM).

Generally for flight missions, there is insufficient time between instrument design and instrument delivery to demonstrate the lifetime with the operation of a flight-like enclosure and detector assembly. Therefore a sensitive estimator is needed that will allow a prediction of performance at EoPM from a measurement taken over several months.

As described in sections 1.3 and 1.4, the polarimeter lifetime for the primary mission is measured as the time between the last gas fill and the time at which energy resolution is less than 30% at 6 keV for an average drift distance of 0.8 cm.

Degradation of gain or resolution occurs due to the outgassing of products that have a high electron affinity that capture the primary electrons while drifting in the electric-field between the X-ray interaction point and the GEM. The larger the drift distance, the more time for the electrons to be captured by the contamination and the more degraded the detected signal. See Figure 5, left.

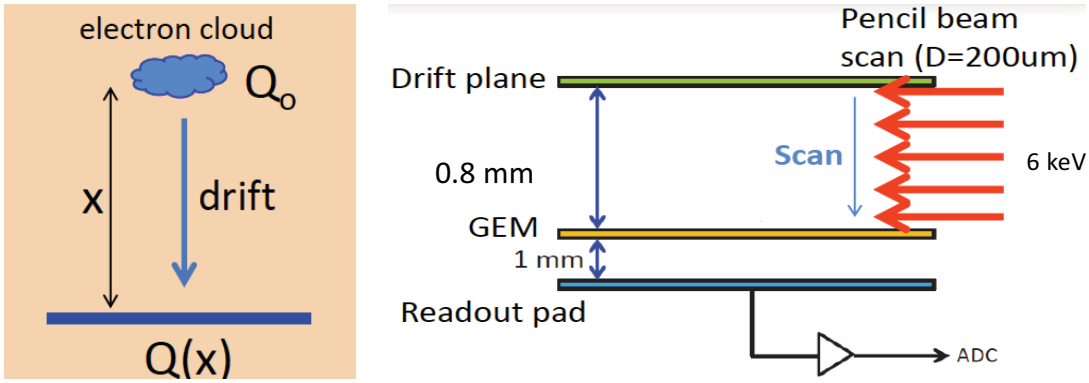


Figure 5 Left: As the electron cloud drifts electrons attach to contaminants and do not reach the detection strips, thus degrading the signal. Right: A test set-up that allows the measurement of the electron capture coefficient, α.

4.1 Method 1 (Energy Resolution)

The concentration of contamination at EoPM was initially determined by measuring the degradation of energy resolution with time using the following procedure:

The detection chamber is pumped out to at least 10^{-7} Torr (goal is 10^{-9} Torr).

The valve to the pump is closed and the 'pressure rate-of-rise' of the system is measured over 15-30 mins from which the outgassing rate is established in T.L/sec.

The system is pumped down again and then filled with 190 Torr of DME.

^{55}Fe X-rays enter the chamber at 0.8 cm above the GEM and the energy resolution of the detector is measured versus time over several days. From the time taken to reach EoPM, one can establish the concentration of contaminants that can be tolerated.

This process was performed four times, for two test set-ups and with differing bake-out durations and pressure rise rates. The chambers and components have relatively high outgassing allowing the measurements to be made over a reasonable time period. The worst case tolerated outgas rate was measured to be 5.0×10^{-9} T.L/sec when corrected for the flight unit volume of 4.7 litres and 16 months lifetime requirement. To add margin for error in the measurements we divide by a factor of 2 to reach 2.5×10^{-9} T.L/sec for the baseline requirement.

4.2 Method 2 (Electron Capture Coefficient)

A more sensitive measure of lifetime is the electron capture coefficient, α, given in equation [1].

$$Q(x) = Q_0 e^{-\alpha x} \quad [1]$$

α is determined from measuring gain versus drift distance at a given X-ray energy, see Figure 5, right. α increases with increasing contamination in the gas. α is then measured overtime time to determine the degradation from outgassing (see Figure 6).

If one measures how long it takes to reach the end of life alpha, the fraction of impurity, C, is given by:

$$C = R.t/(p.V) \quad [2]$$

Where R=outgassing rate, t=time, p=pressure and V=volume of the test set-up.

The required outgassing rate, R_{pol}, for the flight polarimeter is then given by:

$$R_{pol} = pV_{pol}C/\Delta t \quad [3]$$

Where the flight volume is 4.7 litres, Δt=16 months, pressure =190 T.

A small proportional counter detector, consisting of almost all the same materials as the GEMS polarimeter, was installed in an of-the-shelf conflat vacuum chamber. The individual parts were cleaned with IPA prior to assembly and the enclosure with the detector installed was baked out under vacuum ($1x10^{-6}$ T) for 72 hours at 80 °C resulting in a final pressure of $1x10^{-8}$ T. The resulting pressure rate of rise measurement showed an initial rapid increase from 10^{-8} T to $5x10^{-6}$ T where it stabilized, the intermediate rate of $1x10^{-7}$ T.L/sec was assumed. The chamber was then filled with 190 T of DME. The detector gain and energy resolution were measured versus time using an ^{55}Fe source to illuminate the center of the detector. The electron capture co-efficient, α, was also determined by measuring the charge loss at four different heights in the 0.8 cm drift region. Figure 7 shows the variation of alpha with time for two different drift fields, the nominal field (red) and a reduced field (blue) to increase the sensitivity of the measurement.

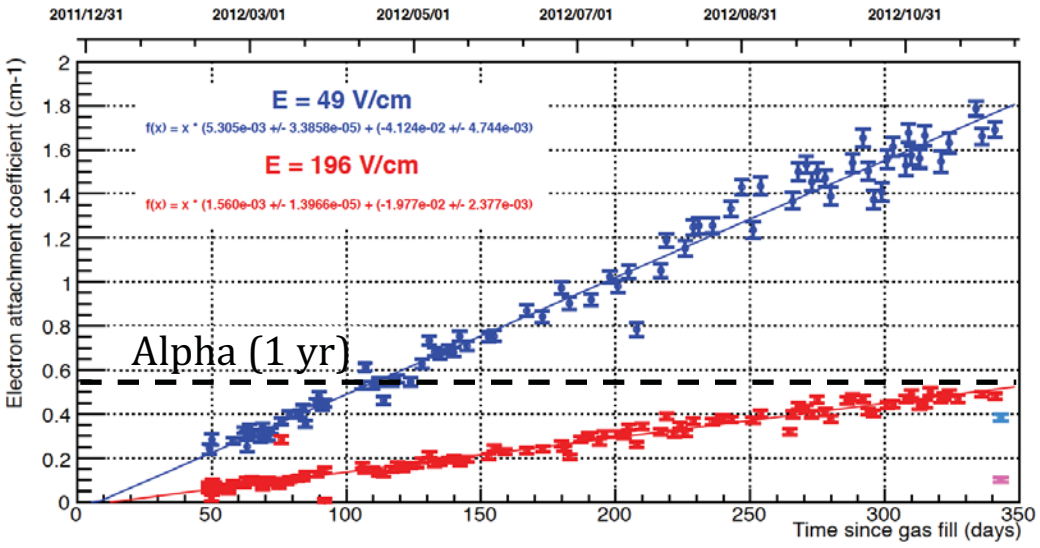


Figure 6 Electron capture coefficient measurements (α) for a small detector using the same materials as a GEMS detector. The parts and chamber had minimal bake-out. Outgassing rate is ~$1x10^{-7}$ T.L/sec. By reducing the drift field the deterioration in performance can be seen much more quickly.

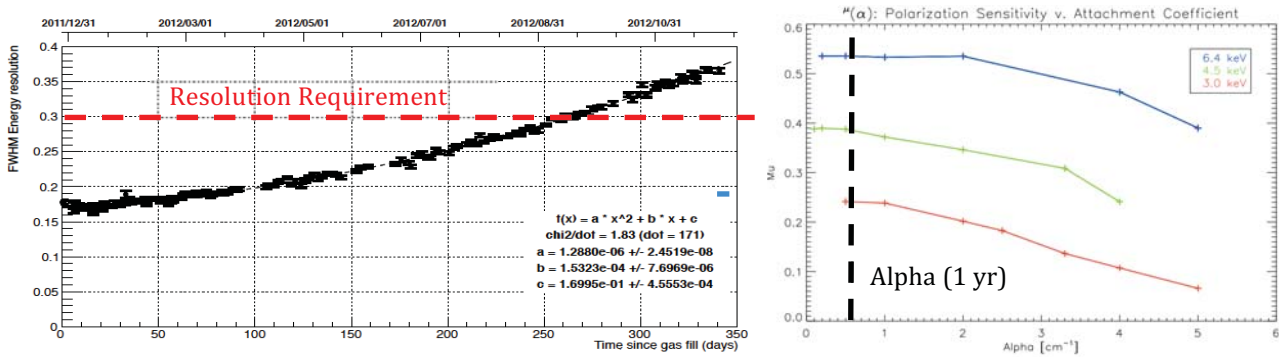


Figure 7 Left: Energy resolution versus time for a small detector using the same materials as a GEMS detector. The parts and chamber had minimal bake-out. Pre-test outgassing rate was ~1x10^{-7} T.L/sec. The energy resolution requirement is met after 260 days. Right: modulation factor, μ, versus alpha, α, from the detector simulation. One can see that even with alpha at the one-year level, the modulation factor has not yet degraded.

Figure 7, left, shows that the energy resolution requirement of 30% is met after 260 days or for an alpha of 0.4. Using 260 days, a test volume of 7.5 litres and an outgassing rate of 1x10^{-7} T, yields a contamination fraction, C, of 1576 ppm. Transferring to the flight volume of 4.7 litres, and lifetime of 16 months yields a required flight outgassing rate of 3.3x10^{-8} T.L/sec which is >5 times more than the initial estimated requirement in section 4.1.

However, if one looks at the relationship between modulation factor, μ, and α, one can see that even after 1 year (α~0.55) there is no degradation in μ, which is the primary performance characteristic of the mission. Considering only modulation, α of at least 1 is acceptable. Nevertheless, this corresponds to a significant loss of charge and although the gain maybe recovered by increasing the GEM voltage it will need further evaluation before the requirement is relaxed to that level.

4.3 Getter Tests

The polarimeter assembly is designed for a getter assembly to be attached via a 1.33" conflat valve. The getter assembly has a nickel pinch-off tube that can be used to pump-out the assembly separate from the polarimeter during activation to prevent contamination. The getter material is SAES 175 that is Titanium 90wt% and Molybdenum 10wt%. It is selected to sorption H_2, CO, CO_2, N_2, O_2 and can also sorb CH_4 at high temperatures. Noble gases are not sorbed. Nominally the polarimeter valve is closed when the getter is activated with a separate pump attach to the pinch-off tube on the getter assembly. Activation occurs in 10 minutes at 900 °C. Once activated the getter is allowed to cool and the pinch-off tube pinched-off. Once the valve is opened to the polarimeter the getter begins to sorb the outgassing materials. Once the material is saturated the getter can be re-activated, however the pinch-of tube would have to be cut open again.

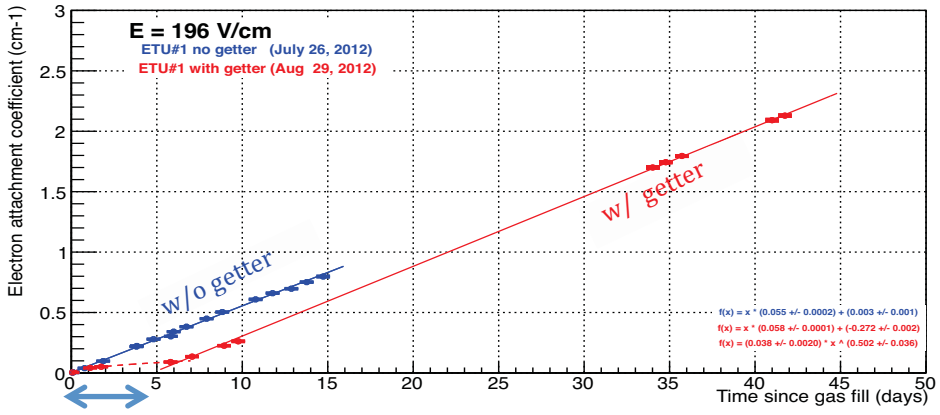


Figure 8 The electron attachment co-efficient was measured for the engineering test unit (ETU) polarimeter both with and without SAES 175 getter in 190 T of DME. The getter is shown to add 6 days of undegraded life for an outgassing rate of 2x10^{-6} T/s into 2.5 Litre volume. For the GEMS flight volume and outgassing rate this yields a 23 yr lifetime.

Although the getter material was selected in consultation with SAES there is very little knowledge regarding its compatibility with DME. The engineering test unit[5] (ETU) polarimeter was used for the assessment of performance, even though is known to only have 16 days of lifetime. Figure 8 shows the result of the test, indicating an additional six days of performance with no degradation, prior to degrading in the same way as with no getter. The pressure rate of rise from the ETU was $2x10^{-6}$ T/s into a volume of 2.5 litres yielding a total sorbed quantity of 2.5 T.L in six days, if one assumes a constant outgassing rate into DME. The GEMS flight polarimeter has three times more getter material and, even with a worst case pressure rate of rise of $1x10^{-8}$ T.L/s, yields a lifetime of 23 yrs. This is similar to the behavior observed on RXTE.

5. BAKE-OUT PROCEDURE

5.1 Flight Bake-out Procedure

Vacuum bake-outs are typically monitored with a quartz-crystal microbalance (QCM). A QCM consists of a crystal exposed to the vacuum environment and allowed to collect molecular contaminants condensable at the crystal temperature. The amount of deposited mass can be obtained from the change in the crystal frequency. However, the sensitivity of the QCM was deemed to be insufficient to measure outgassing at the requirement levels. The outgassing rate was instead determined by performing a pressure rate of rise in which the pump valves were closed and the pressure rise was monitored over a 24 hour period. The standard processing sequence consisted of the following steps:

Pre-clean the components using isopropyl alcohol (IPA) and/or toluene.

Double bag the components and deliver to the bake-out room. Sensitive components were transported in a nitrogen purged dry box.

Wipe down bake-out trays and, if required, ultra-high vacuum (UHV) aluminum foil with IPA.

Load the components on bake-out trays, photograph, and carefully place in the chamber.

Attach two thermocouples to the opposite ends of the bake-out tray assembly.

Seal the chamber with a new copper gasket and pump down.

Once at sufficiently low pressure (~$1x10^{-5}$ T), begin a slow temperature ramp up by adjusting variable transformers (variacs) through several discrete steps (for example, Lo->1/4->1/2->3/4->Full for a 200 °C bake).

Continue baking at the prescribed temperature (200 °C for majority of parts) until pressure change becomes negligible. The typical bake period was five days for metal components and ten days for LCP and PEEK parts.

Take residual gas analyser (RGA) measurements with and without the electron multiplier once a day.

Prior to terminating the bake-out, take the final RGA measurements and then begin a slow ramp down to 40 °C, the maximum polarimeter operating temperature.

Allow pressure and temperature to stabilize and then begin the outgassing certification by closing valves to the RGA and the turbo vacuum pump. The turbo pump is left powered on.

Allow the pressure to rise over a minimum period of 24 hours and obtain an RGA with the valve closed if pressure allows (less than $1x10^{-5}$ T).

Open the valve to the pump and allow the pressure to stabilize. Obtain another RGA scan with the valve open.

If the pressure rate of rise meets requirements, turn off heaters, backfill the chamber, and remove samples from the chamber. Double-bag in clean-room compatible bags prior to transport to dry box. Parts are typically stored in <20% humidity, nitrogen purged dry box.

5.2 Bake-out Facilities

Measurements have been made using five different facilities. The initial bake-outs were performed in the "*Excalibur"* bake-out box. This chamber is equipped with four QCMs. However, the sensitivity of the QCMs was not sufficient to confidently determine the outgassing rate. A number of time-temperature bake-outs were performed for the fasteners, washers and other stainless steel hardware in the "*Harpold*" stainless steel chamber. The assembled flight enclosure was

baked in an atmospheric pressure oven with the enclosure directly pumped with a turbo pump (Figure 10, right).

The two primary bake-out facilities used were a commercial of the shelf 10" stainless steel "*Mahaffy"* chamber and a larger custom 12" aluminium "*Atlas*" chamber. These chambers are shown in Figure 9. The chambers were pumped out with turbo pumps backed with a two-stage backing pump. By various valve configurations, the chambers could be backfilled with nitrogen and pumped back down without powering down the turbo, which prevents water absorption onto the turbo blades each time.

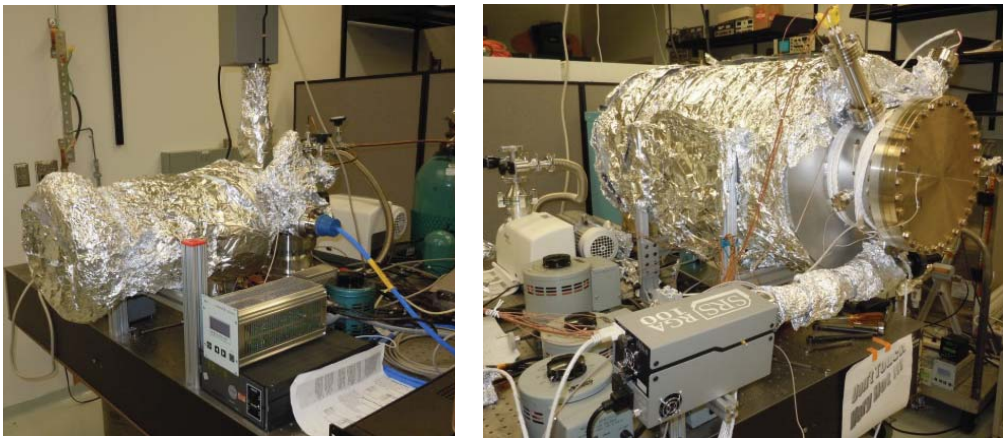


Figure 9 Bake-out facilities: Mahaffy stainless steel 10" chamber (left), Atlas 12" aluminium chamber (right) with the door foil removed for leak checking.

The full-up polarimeter assembly is baked-out in an oven at atmosphere (Figure 10). A vacuum is pulled on the polarimeter itself, or a purge of Argon can be used to drive water off the interior walls of the polarimeter, while the oven heats the exterior to ~80 °C. The maximum temperature is limited by how taught the GEM LCP can be held by the frame knife-edge before creeping with the differing CTE's for the frame and LCP materials.

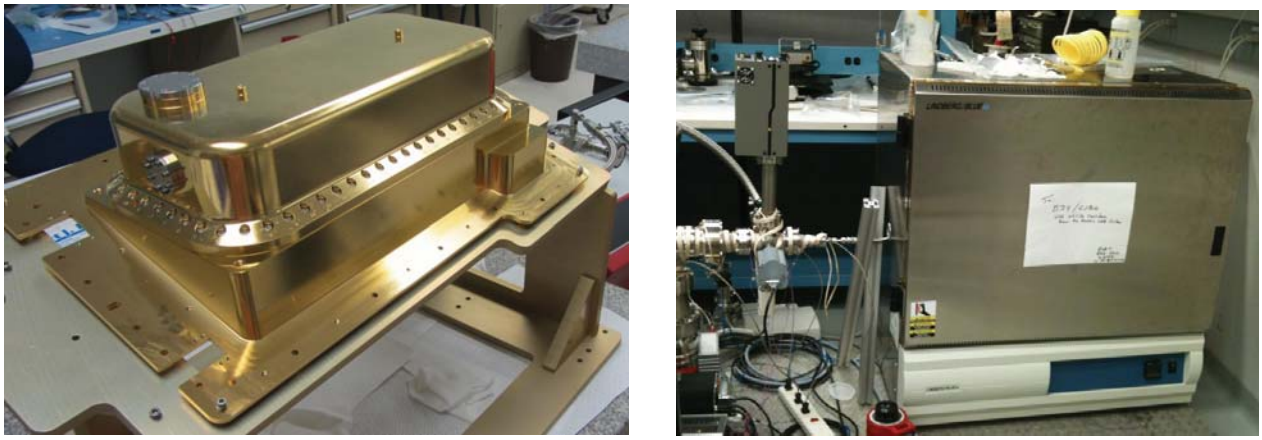


Figure 10 Polarimeter Assembly (left) and bake-out oven with residual gas analyzer (RGA) and pumps (right) attached to the polarimeter inside the oven.

5.3 Data Reduction

The chambers were equipped with ion gauges and data acquisition software that recorded pressure and temperature data to an output file at a specified frequency (typically once per minute). The data was subsequently imported into Excel, and the rate of rise, in T.L/s, was obtained from the slope of the pressure curve,

$$r = \left(\frac{p_2 - p_1}{t_2 - t_1}\right) V_c \qquad [4]$$

where V_c is the volume of the vacuum chamber. The volumes were estimated as 12.4 L for Mahaffy and 144 L for Atlas.

The pressure rise was generally not linear. Instead, the pressure typically traversed through three regimes: an initial slow ramp up to ~1x10^{-7} Torr, rapid linear rise to ~ 8x10^{-6} Torr, and finally pressure stabilization indicated by an asymptoting pressure. In general, the pressure rise was computed at the steepest part of the pressure rise.

The variation in outgassing rate with background pressure is of importance in estimating the lifetime contribution. The outgassing is expected to decrease as the background pressure increases due to the increase in collisional cross-section. The average distance between molecular collision, the free path scales as $\lambda = 1/(n\sigma)$, where n is the density and σ is the collision cross-section. We see that for many of the considered cases, at background pressure around 10^{-5} Torr the pressure had stabilized, indicating a near-zero net outgassing rate. This reduction in pressure increase could be attributable to a combination of return flux to the chamber walls and included components, as well as to potential chemical interactions between the chemical constituents. The interaction between the outgassed species and the 190 T (expected operating pressure) DME is not known. Hence, in order to perform a conservative estimate, the representative average pressure rise rate was computed for the 24 hour period. These rates are summarized in Table 6-1.

It is important to note that in the outgassing calculations, the chamber background rate was not subtracted. The initial assumption driving this decision was that the contribution from the chamber and support equipment was minimal and could thus be neglected. Unfortunately, this assumption only held for the Mahaffy chamber. The Atlas chamber continued to demonstrate empty chamber pressure-rise rates comparable to the unit-certification levels. In addition, the chamber continued to suffer from a number of small leaks that introduced a virtual outgassing source. As such, the outgassing rates from the Atlas chamber are inconclusive.

Besides the pressure measurements, the bake-outs were also monitored with a residual gas analyser (RGA). The Mahaffy and Atlas chambers were equipped with SRS RGA200 and SRS RGA100 units, respectively. Both units contained the optional electron multiplier (CEM). For consistency, only the data up to 100 amu/q were considered. Prior to taking data, the RGA was powered on and the filament was turned on. The head was then outgassed, reset, and calibrated. One scan was then performed and discarded; the purpose of this scan was to warm up the filament. Three scans were subsequently averaged to obtain the first set without the CEM. The electron multiplier (CEM) was then activated, and another averaged sample consisting of three scans was taken. The CEM reduced the noise floor from 1x10^{-10} Torr to 1x10^{-13} Torr, allowing a better resolution of trace species.

6. RESULTS

6.1 Sample Measurements with a TQCM

Early RGA measurements indicated that water was the biggest outgassing component by at least an order of magnitude implying that baking and purging with CO_2 or Argon will reduce the outgassing significantly. This was confirmed by component bake outs using a TQCM. Summing component bake-outs of 10-15 days at 120 °C and extrapolating to an operating temperature of 40 °C, the total outgassing requirement was close to being met. As a result the flight bake-out temperature was increased to 200 °C.

6.2 Field-cage Assembly Design

The field-cage design was a concern to the contamination engineers due to the PEEK isolators being trapped between the magnesium field-shaping yokes. To mitigate against potential long term slow outgassing, the flight design was upgraded from the ETU to include channels along the length. To keep the field uniform the channels do not penetrate all the way through to the active volume (Figure 11).

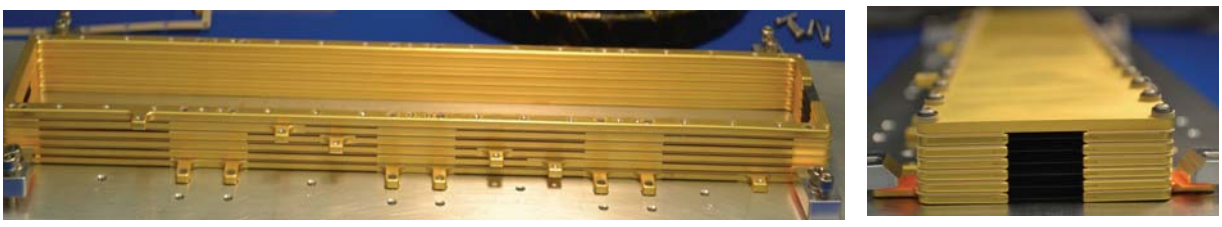
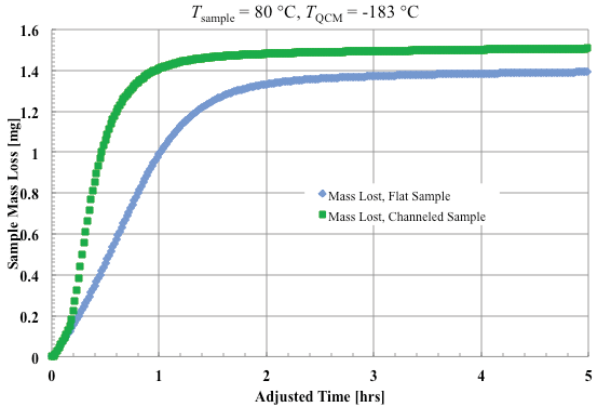


Figure 11 Flight field-cage design showing the special channels to allow the trapped PEEK to outgas more efficiently. Left: edge on view showing the channels do not pentrate into the active volume. Right: end on view.

Figure 12 shows the total mass loss for two test samples, one with channels (green) and one without the channels (blue). One can see that the channeled samples are a big improvement and outgassed greater quantity and much faster than the non-channeled samples.



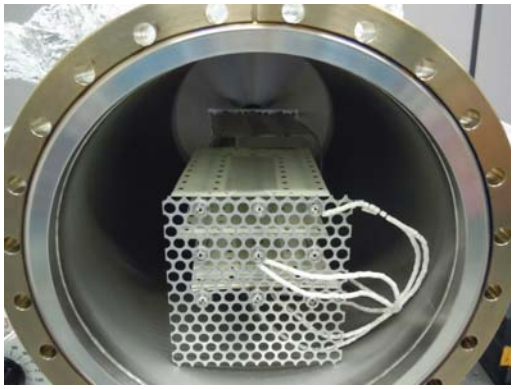


Figure 12 Left: Total mass loss for channeled and non-channeled field cage samples. The channels allow for greater outgassing in a much shorter period of time. Right: LCP strips and flex cables inside the Mahaffy chamber with ceramic isolated thermocouples and stainless steel racks.

During the component bake-outs we found that baking at 200 °C shrunk the GF30 PEEK spacers. The root cause was determined to be lack of stress relief during fabrication as the thin spacers had to be machined from 1-inch thick material. Baking the spacers at 125 °C did not shrink them, however the outgassing was still relatively high after the nominal 15 days. Additional spacers were machined from virgin PEEK sheet material which was much more successful and able to be baked-out at the higher temperature of 200 °C without issue.

6.3 Flight component bake-outs

A summary of the outgassing rates measured at the maximum operating temperature of 40 °C, for each of the flight component are listed below. Each sub-set has been scaled relative to the number of components actually in the polarimeter i.e. 4 strips, 4 cables etc., and adjusted for the flight volume.

Table 6-1

Component	Material	Bake-out Duration	Outgassing Rate @ 40 C
ROB Cable & Strips	LCP	9d @ 200 C	2.0e-10 T.L/sec
ROB clamps & connectors	PEEK	7d @ 200 C	1.8e-10T.L/sec
ROB isolators/spacers	PEEK	7d @ 200 C	1.0e-10 T.L/sec
ROB & GEM Frames	Ti & CuW	4d @ 200 C	1.8e-11 T.L/sec
GEMs	LCP/Cu	5d @ 200 C	2.0e-10 T.L/sec*
Fasteners	Stainless Steel	1d @ 260 C	4.8e-10 T.L/sec
Valves	Stainless Steel	9d @ 200 C	2.4e-10 T.L/sec
Wires	Au/Cu	8d @ 200 C	1.0e-10 T.L/sec
Field cage Assembly	Mg/PEEK/SS	6-7d @ 200 C	1.2e-10 T.L/sec**
Thermal straps, pinch-off tube, Be Windows	Cu, SS, Be	14d @ 200 C	6.4e-10 T.L/sec
Total			**2.3e-9 T.L/sec**

*$3x10^{-9}$ T.L/sec measured in Atlas and background dominated, expect closer to strip ~$2x10^{-10}$ T.L/sec

** Field shaping frames & fasteners 2.4 $x10^{-11}$ T.L/sec, PEEK isolators expected to be similar to ROB $1x10^{-10}$ T.L/sec

Several outgassing measurements were made for the GEMs however all of them were limited by the background of the Atlas chamber, and the Mahaffey chamber was too small for the uncut GEM sheets. For the total, the outgassing rate for the strips and cables was used as an upper limit for the GEM outgassing. Similarly, the field-cage PEEK parts were also baked in the Atlas chamber. The field-cage assembly rate is comprised of the field-shaping yokes, the fasteners and then an estimate for the PEEK isolators based on the ROB PEEK isolators.

The total outgassing from all the components is 2.3×10^{-9} T.L/s but does not include the outgassing from the enclosure although expected to be low and similar to the background from the bake-out chambers. The entire polarimeter assembly will be baked out for 20-30 days at 80 °C with an Argon purge. This will remove surface moisture picked up during the final assembly.

6.4 Polarimeter Seals

The polarimeter uses four off-the-shelf Inconel c-seals on the cover and baseplate for the two beryllium windows, the pressure transducer and the purge port. These were leak tested to less than 1×10^{-12} std cc/sec, which is close to perfect. The polarimeter has two 1.33" copper conflat gaskets to the getter valve and the gas/pumping valve that were also leak tested to less than 1×10^{-12} std cc/sec. The large rectangular seal between the cover and the baseplate (Figure 13, left) is a custom lead-plated inconel c-seal. This was leak tested to 5×10^{-10} std cc/sec which is better than the requirement. To achieve this IPA was used as a lubricant on the seal to allow it to move freely into place. If Bray 815Z is used the leak rate is reduced to $<1 \times 10^{-12}$ std cc/sec. Initial life tests with a 1.5" disk lightly coated with 815Z included in the chamber showed no additional degradation, however residual concerns that the oil will be transferred onto critical surfaces still remain.

Figure 13 Left: Enclosure cover showing the custom rectangular c-seal. Right: Polishing tool and the polished window interface for the round c-seal.

7. CONCLUSION

We have demonstrated that measuring the electron attachment co-efficient, α, versus time allows for a quicker interpretation of the polarimeter degradation (lifetime) than energy resolution or gain. The interpretation can be sped up further by decreasing the drift-field. Measurements of energy resolution and α for two different drift-fields have been made for a detector containing most of the materials included in the GEMS polarimeter. The energy resolution exceeded 30% at ~260 days, however according to the detector simulation there is no deterioration in μ until $\alpha>1$ which will not be reached until ~ 2 years. One must note however, that at $\alpha>1$ the gain is significantly reduced but can be compensated by turning up the voltage on the GEM.

Measurements with SAES 175 getter and the engineering test unit polarimeter indicate that the GEMS getter design will provide >23 yrs of lifetime if a worst case beginning of life outgassing rate of 1×10^{-8} TL/s is achieved. This is four times higher than currently required.

The outgassing measured for the component bake-outs is 2.3×10^{-9} T.L/s less than the requirement (2.5×10^{-9} T.L/s). The c-seal leak rates also exceed the requirement and could be further improved with the use of BRAY 815Z.

These tests have demonstrated that, with the additional full-up assembly bake-out (80 °C for 30 days) and the getter, the GEMS polarimeter lifetime will greatly exceed the 16 month lifetime requirement.

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